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PROGRESS REPORT OF THE SUBCOMMITTEE ON CONSOLIDATION OF MATERIALS IN EARTH DAMS AND THEIR FOUNDATIONS OF THE COMMITTEE ON EARTH DAMS OF THE SOIL MECHANICS AND FOUNDATIONS DIVISION

SOIL MECHANICS DIVISION

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COMPACTION OF COHESIVE SOILS

PROGRESS REPORT OF THE SUBCOMMITTEE ON CONSOLIDATION OF MATERIALS IN EARTH DAMS AND THEIR FOUNDATIONS OF THE COMMITTEE ON EARTH DAMS OF THE SOIL MECHANICS AND FOUNDATIONS DIVISION

Synopsis

The intent of this progress report is to broaden the scope of the compaction problem to its four phases—laboratory practice, the compaction of fills, compaction requirements as related to design, and the performance of fills. Properly, the correctly designed embankment should be the result of judiciously blending the precise knowledge that will satisfy the solution of all four phases in each instance. This objective, however, presumes learning far beyond the present scope; but it does indicate a goal that can be approached by continuing study and investigation. Therefore, this report is pointed toward implying the nature of needed investigation, and enlisting greater assistance from the profession.

Laboratory Practice

Since 1933, when R. R. Proctor,[1] M. ASCE, first published his principles of soil compaction, there has been an inordinate amount of work done in studying the workability of soils in laboratory apparatus, most of which has added little to Mr. Proctor's original understanding of the subject. It is suggested, therefore, that soil analysts should cease laboring on variations of Mr. Proctor's early work and turn these efforts to the more difficult studies of the performance of soils in embankments.

To enable the experienced engineer to establish reasonably accurate ranges of workability, the adoption of a standard compaction test—such as that of the American Association of State Highway Officials (AASHO No. T134–45)—is

Note.—Please forward all comments on this report directly to Chairman Robert R. Philippe, Ohio River Div. Laboratories, Corps of Engrs., U. S. Army, Cincinnati 27, Mariemont, Ohio.

[1] "On the Design and Construction of Rolled-Earth Dams," by R. R. Proctor, *Engineering News-Record*, August 31, 1933, p. 245; September 7, 1933, p. 286; September 21, 1933, p. 348; and September 28, 1933, p. 372.

proposed for identification purposes. It must be clearly understood, however, that the adoption of this standard test does not set the compaction requirements for any embankment. The fundamentals of compaction of cohesive materials, as they are now revealed by conventional laboratory tests, are as follows:

1. For a given method of compaction, a maximum unit weight of a given soil occurs at an optimum water content.
2. With standard Proctor compaction, the optimum water content is different for different soils but is approximately 3% drier than the Atterberg plastic limit.[2]
3. With each change of compactive effort, there is a change of the maximum unit weight of the soil, and a corresponding change in the optimum water content.
4. As the compactive effort increases, the maximum unit weight increases and the optimum water content decreases. Conversely, if the compactive effort decreases, the maximum unit weight decreases and the optimum water content increases.
5. As the compactive effort is increased, the unit weight will approach an ultimate value as a limit.[3] This ultimate, however, is usually far beyond practical limits of achievement.
6. With wetter than optimum water content for a given compactive effort, the maximum unit weight obtainable is readily achieved, and added effort will not appreicably increase that maximum unit weight.
7. At, or drier than, the optimum water content for a given compactive effort, increasing that effort by added load repetitions will increase the unit weight until new maximums are achieved.[4,5]
8. To achieve these new maximums, it appears to be more efficient to increase the unit pressure of the compactive unit than to increase the number of applications of the original effort.[6]
9. Soils, although compacted, sometimes exhibit tendencies to swell,[7] consolidate further,[6] or otherwise change their properties,[8] depending on the type of soil and the myriad of conditions that surround it.

The Compaction of Fills

There is substantial evidence to indicate that the elements of laboratory compaction are correct when applied to the placement of fills by rolling. On the other hand, the meager evidence available indicates that precise correlation does not exist between the compaction of a given soil by any laboratory procedure and the compaction of the same soil in a fill.

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[2] "Soil Mechanics in Highway Construction," by K. B. Woods, *Civil Engineering*, January, 1937, p. 5.

[3] "Soil Compaction Experiments Point Way Toward Stronger, More Economical Subgrades," by Warren D. Curtis, *ibid.*, July, 1947, p. 32.

[4] "Tests of Compacted Clay Soils Provide Highway Design Guides," by Henry C. Porter, *Engineering News-Record*, November 29, 1945, p. 74.

[5] "Compaction of Earth Embankments," by L. W. Hamilton, *Proceedings*, Highway Research Board, National Research Council, Vol. 18, 1938, p. 142.

[6] "Field and Office Control of Earth Embankments," by R. R. Philippe, U. S. Engr. Office, Pittsburgh, Pa., November 18, 1939.

[7] "Effect of Moisture of Compacted Soils Revealed by Laboratory Tests," by Henry C. Porter, *Engineering News-Record*, August 23, 1945, p. 101.

[8] "Discussion by R. R. Proctor of "Military Airfields: A Symposium," *Transactions*, ASCE, Vol. 110, 1945, p. 799.

Although he indulges in arithmetical manipulations to correct for materials contained on a No. 4 sieve, Mr. Proctor has presented an interesting curve[9] which is perhaps the first attempt to show the difference that can be expected between laboratory and field compaction. Later (in 1947), the United States Waterways Experiment Station at Vicksburg, Miss.,[10] presented the results shown in Fig. 1 for samples containing 11% clay, 3% silt, and 86% sand (plastic limit (PL), 16; liquid limit (LL), 18; and plasticity index (PI), 2). Although these tests contained variables which far from satisfied the engineers who conducted them, the variations between field and laboratory methods are pronounced. Later and more conclusive tests were conducted by the same group, a summary of which work was reported by W. J. Turnbull and Gayle McFadden,[11] Members

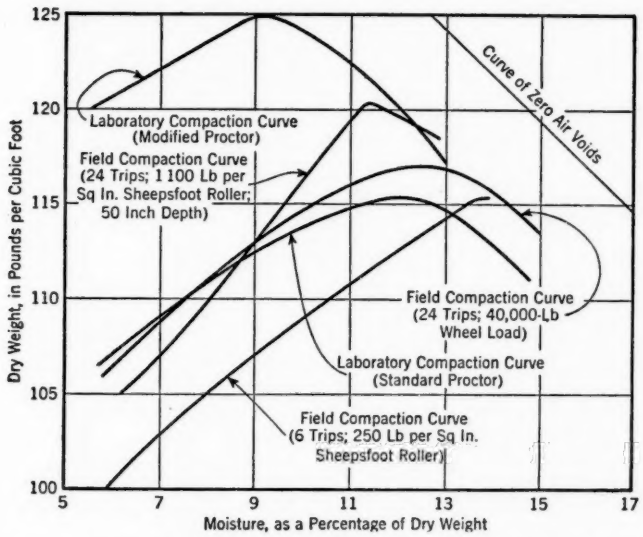

FIG. 1.—COMPARISON OF LABORATORY AND FIELD COMPACTION, CLINTON TEST SITE, CLINTON MISS., BY UNITED STATES WATERWAYS EXPERIMENT STATION, VICKSBURG, MISS.

ASCE. These studies show severe deviations of field compaction results from those of laboratory compaction. Furthermore, two types of soils yielded different comparisons, the most disturbing of which is the tendency of the field compaction curve to crowd the zero air voids curve for the more cohesive materials. Although the comparisons are not deliberately made, D. J. MacLean and F. H. P. Williams[12] show results of field studies, many of which crowd the zero air voids curve. Field results obtained by the subcommittee chairman

[9] Discussion by R. R. Proctor of "Selection of Materials for Rolled-Fill Earth Dams," by Charles H. Lee, *Transactions*, ASCE, Vol. 103, 1938, p. 51, Fig. 22.

[10] "Soil Compaction Investigation," Appendix D, Subgrade Compaction Test, U. S. Waterways Experiment Station, Vicksburg, Miss., June 18, 1947.

[11] "Field Compaction Tests," by W. J. Turnbull and Gayle McFadden, *Proceedings*, 2d International Conference on Soil Mechanics and Foundation Eng., Rotterdam, Vol. 5, 1948, p. 235.

[12] "Research on Soil Compaction at the Road Research Laboratory (Great Britain)," by D. J. MacLean and F. H. P. Williams, *ibid.*, Vol.-IV, 1948, p. 247.

during construction, with 35% clay, 54% silt, and 11% sand (PL, 28.6; LL, 44.6; and PI, 16), are presented in Fig. 2. They show a typical spread of results but with marked tendency for deviation from the laboratory compaction curve and crowding the zero air void condition. From these meager results it is thought the following conclusions can be stated:

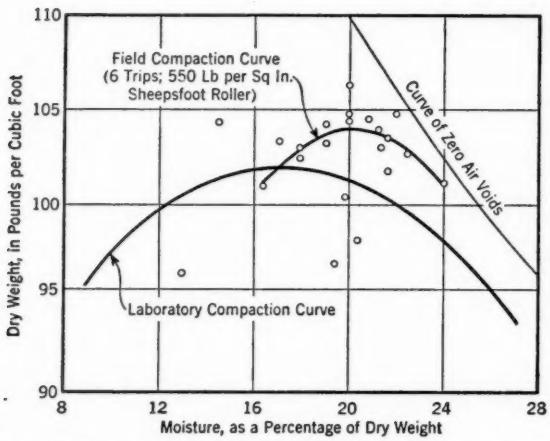

FIG. 2.—COMPARISON OF LABORATORY AND FIELD COMPACTION, EMBANKMENT AT WOLF CREEK DAM, IN KENTUCKY

1. It is probable that each method of compaction on any soil will produce a unique result.

2. It is unlikely that the reaction of any given soil to field compaction can be predicted accurately from laboratory tests, although they may be sufficiently accurate for many practical applications.

3. Field compaction, wetter than optimum for the equipment, leads to higher degrees of saturation than are indicated by laboratory tests. It is suggested that wider recognition and understanding of these statements may ease the confusion of many a puzzled operator being guided by laboratory tests.

COMPACTION REQUIREMENTS AS RELATED TO DESIGN

Designs of embankments can be grouped into three general classifications—

a. The proportions of the embankment are dictated by conditions not related to compaction;

b. The compaction methods are devised to fit design assumptions (the classical design);[13] and

c. The benefits of compaction are fully exploited to trim embankment proportions.

Class *a* is now expanded; class *b* is discussed subsequently under the heading, "Performance of the Classical Case"; and class *c* is allowed to remain as a challenge for more economical design.

In many instances earth dams have been built on poor foundations, making it necessary to flatten slopes or add berms to achieve stability. Such foundations are often unconsolidated plastic soils, which when loaded will settle and move. For example, observations on six such embankments in the Muskingum system,[14] ranging in height from 43 ft to 76 ft, showed settlements of from 1.8 ft

[13] "Fundamentals of Soil Mechanics," by D. W. Taylor, John Wiley & Sons, Inc., New York, N. Y., 1948, Chapter 16.

[14] "Practical Soil Mechanics at Muskingum," by Theodore T. Knappen and Robert R. Philippe, *Engineering News-Record*, March 26, 1936, p. 453.

to 4.2 ft, with horizontal movements as much as 1.3 ft and with no outward signs of distress. In such cases it appears desirable to select materials for the embankment and compact them to strain compatibly with the foundation. This principle, practiced at the earth dams of the Central Nebraska Project, Berlin and Mosquito Creek dams, resulted in a deliberate reduction in compaction effort with complete success.

In rarer instances, for dams and very often for levees, the degree of obtainable compaction is controlled by the high moisture content of the available borrow materials. It is sometimes possible to place such fills by removing ballast from rollers, compacting with tractors, or other similar expedients. The section of the embankment must be adjusted to the results. This practice was followed successfully at Mohicanville Dam (1936) in Ohio.

There are many examples in which the materials used for borrow are weak or decomposed rocks which are processed into a soil-like mass for construction. Decomposed granites, gneisses, and schists were so used at Glenville and Nantahala dams in North Carolina[15] and at Aqua Fria and Mariposa dams in Venezuela, and were contemplated for use at Buggs Island Dam in Virginia (currently under construction). Silt stones, indurated clays, and silt and clay shales ranging from decomposed to fresh rock have been so used at many places, including Leesville Dam in Ohio, Crooked Creek and Tionesta dams in Pennsylvania, Denison Dam in Texas, and Great Salt Plains Dam in Oklahoma. An extreme, in the use of this type of construction, was at Youghiogheny Dam in Pennsylvania, where 3,200,000 cu yd of rock excavated from the spillway was processed through crushers and used in the embankment.[16] Mr. Proctor[9] reports the use of a "metamorphosed dioritic gneiss" in California. In many of these instances, the amount of processing necessary to render such materials into a regular impervious soil-like mass builds into them stability beyond ordinary requirements. Furthermore, this processing need not even be similar to that usually required for compaction.

Finally, consider the case in which drainage provisions in the embankment are so extensive as to render any compaction requirements structurally superfluous. With sufficient drainage, the process of consolidation can keep abreast of construction progress or can sufficiently outstrip the process of saturation. An earth diaphragm in a rock-fill dam is a good example, and Nantahala Dam[15] is outstanding evidence of the success of such thinking. The validity of exploiting this principle was demonstrated successfully at Dewey Dam in Kentucky (discussion by T. A. Middlebrooks of an address by O. J. Porter on "Vertical Sand Drains for Stabilization of Compressible Foundations," presented at the ASCE Annual Meeting in New York, N. Y., on January 22, 1948) where vertical sand drains were used to reclaim all unsuitably constructed sections of the embankment. Under such conditions of sufficiently rapid drainage, field compaction becomes largely a construction expedient and a method of curbing undesirable movements.

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[15] "Diversion Tunnel and Power Conduit of Nantahala Hydroelectric Development," by D. J. Bleifuss, *Proceedings*, ASCE, December, 1949, p. 1409.

[16] "Belt Delivers Fill for Earth Dam," *Engineering News-Record*, December 3, 1942, p. 75.

The purpose in citing all these cases is to demonstrate many instances in which the normal concepts of compaction can be misapplied, often at the expense of over-all stability and usually with greater cost of construction.

Performance of the Classical Case

There still remains the so-called classical case, where embankments are designed and compacted to conform to that design. In addition, if the design is correct, the compacted soils must perform within the limits of that design for the embankment to be satisfactory.

Mr. Philippe suggests[17] that compaction requirements be divorced from the workability of the soil, and that they be based entirely on the same criteria used in design. As a simplified illustration, the consideration of an embankment conforming to the concept of analysis known as the "method of slices"[18] is proposed. The shearing strengths used therein are based on tests of suitably prepared specimens of borrow materials. If it is assumed that at a given density a soil has a unique shearing strength, the minimum densities which yielded the strengths to satisfy the design are in reality the lower limits of compaction requirements. Therefore, a consolidation test on a parallel specimen will serve to define these limits. The minimum limits so obtained on three specimens are illustrated by the dotted lines in Fig. 3, the characteristics of which are presented in Table 1. If the void ratios are converted to dry unit weights, this part of Fig. 3 is in satisfactory form for field control.

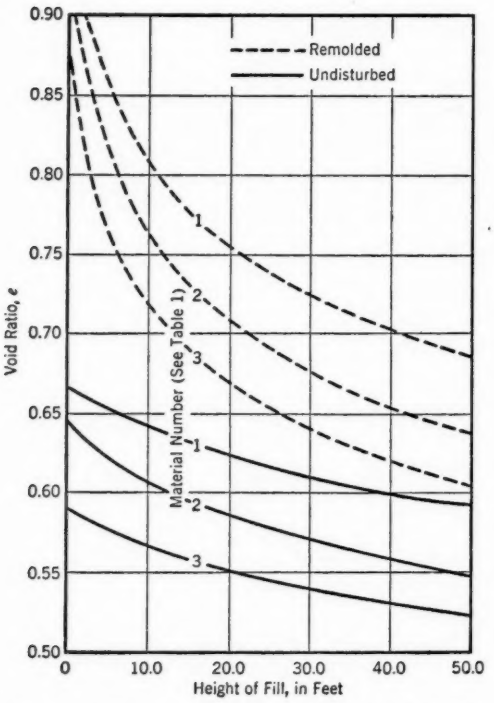

Fig. 3.—Static Compaction Curves, Levee Extension, Ceredo to Kenova, W. Va.

Also given in Fig. 3 are the results of similar tests made on undisturbed specimens taken from the same embankment placed in 6-in. layers, compacted with a sheepsfoot roller (250 lb per sq in.) and completed seven months prior to

[17] "Adaption of Locally Available Materials for Use in Construction of Earth Dams," by Robert R. Philippe, *Proceedings*, 2d International Conference on Soil Mechanics and Foundation Eng., Rotterdam, Vol. IV, 1948, p. 267.

[18] "Analysis of Homogeneous Earth Dams by the Slices Method," by Donald W. Taylor (publication as a *Proceedings-Separate* pending).

sampling. In the meantime, the levee had satisfactorily withstood one severe flood. The height of levee is 26 ft. From these and other tests the following statistics were compiled:

Description	Percentage
Percentage of static compaction requirements obtained	106.3
Average water content required by static compaction	27.7
Average water content in place	22.3
Percentage of Proctor maximum weight obtained	97.8
Average water content at Proctor optimum	17.9

Although the fill has an average water content 4.4% greater than the Proctor optimum, shearing tests on undisturbed specimens indicate ample stability by conventional analysis, as does the performance to date.

It is readily admitted that the method as illustrated is not complete. Such factors as seepage forces and time-density effects must be taken into account, not only during placement but also in design. The principle of the method is demonstrated and probably can be modified to keep abreast of advances found by explorations and design. This statement stresses the fact that deficiencies of understanding are not attributable to insufficient methods of control, construction, or design but rather to the fundamental properties of soils in embankments. Therefore, a need is implied for a two-way effort—the study of the properties of soils and a study of the reaction of embankments.

The first of these is the province of any observer and investigator, just as long as the studies are evaluated in absolute terms. It is suggested, therefore, that the use of penetration ratios, the California Bearing Ratio, cone penetration, etc., be abandoned for basic study as rapidly as possible. Serviceable as such relative values may be, they prohibit any attempt at rational analysis. It would be remiss not to point out that many investigators are now dealing with this basic study. Simply to present an example of such efforts, a selected part of an investigation conducted by the Waterways Experiment Station is presented in Fig. 4. In spite of the purposely avoided details, one is impressed by the large variety of methods by which stability is indicated, and how the process of consolidation increases the range of stability when wetter than optimum.

TABLE 1.—Material Used for Levee Extension, Ceredo to Kenova, W. Va.

Material No.	Atterberg Limits			MIT[a] Classification (%)		
	PL	LL	PI	Clay	Silt	Sand
1	27.4	40.4	13.0	32	53	15
2	26.2	39.4	13.2	22	55	23
3	23.7	37.5	13.8	23	49	28

[a] Massachusetts Institute of Technology, Cambridge, Mass.

A study of the reaction of embankments, however, is the restricted province of the owner, principally the agencies of the government who, by their volume of work, can justify such expenditures for improvement. Both the Bureau of Reclamation (United States Department of the Interior) and the Corps of Engineers (United States Department of the Army) are conducting many such

investigations which, as the quality of measuring instruments improves, give promise of a wealth of new information on all phases of the embankment problem. Although such studies require years to complete, the Bureau of Reclamation has already obtained some very significant results reported by F. C. Walker, M. ASCE, and W. W. Daehn,[19] Jun. ASCE. These show the

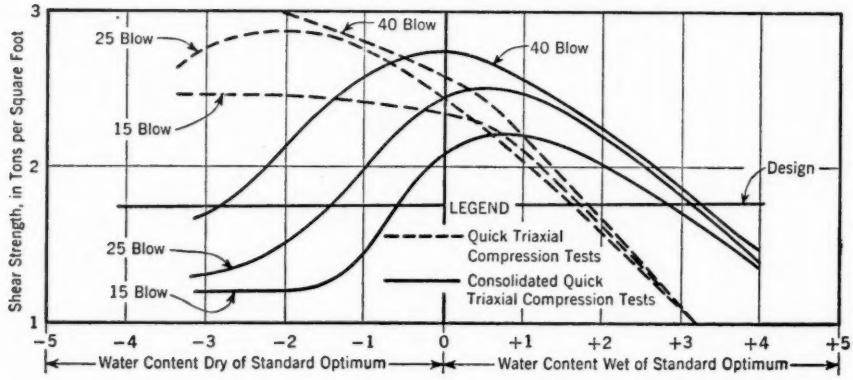

FIG. 4.—EFFECT OF COMPACTIVE EFFORT AND WATER CONTENT ON SHEAR STRENGTH (NORMAL LOAD, 3.0 TONS PER SQ FT)

rapid development of piezometric systems in embankments, not unlike those found in other land masses, with very rapid responses to changes in reservoir level. Although all the embankments considered were placed deliberately on the "dry side," some pressures greater than hydrostatic are recorded. Unfortunately, no similar studies are yet available for embankments placed on the "wet side" of optimum; however, Kenneth E. Fields and William L. Wells,[20] Assoc. Members, ASCE, observed during construction of an embankment the loading of a foundation of saturated clay wherein full hydrostatic equivalents were recorded. Although these tendencies are not to be unexpected, the inability of engineers to predict such results accurately and to exploit them fully is disturbing.

CONCLUSIONS

In conclusion, the subcommittee suggests the following:

1. The standard Proctor compaction test should be adopted to enable the engineer to establish reasonably accurate ranges of workability for cohesive soils, with procedure conforming to that designated by the AASHO test No. T134–45;

2. A complete report on field and laboratory compaction methods should be prepared; and

[19] "Ten Years of Pore Pressure Measurements," by F. C. Walker and W. W. Daehn, *Proceedings*, 2d International Conference on Soil Mechanics and Foundation Eng., Rotterdam, Vol. III, 1948, p. 245.

[20] "Pendleton Levee Failure," by Kenneth E. Fields and William L. Wells, *Transactions*, ASCE, Vol. 109, 1944, p. 1400.

3. The weight of investigational effort should be shifted from the study of the workability of soils, to a study of the fundamental design properties of soils compacted in embankments.

Respectfully submitted,

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O. J. PORTER
W. L. SHANNON
W. J. TURNBULL

ROBERT R. PHILIPPE, *Chairman*

Subcommittee on Consolidation of Materials in Earth Dams and Their Foundations of the Committee on Earth Dams of the Soil Mechanics and Foundations Division

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